Radiation Damage and Other Measurements of LBNL CCDs

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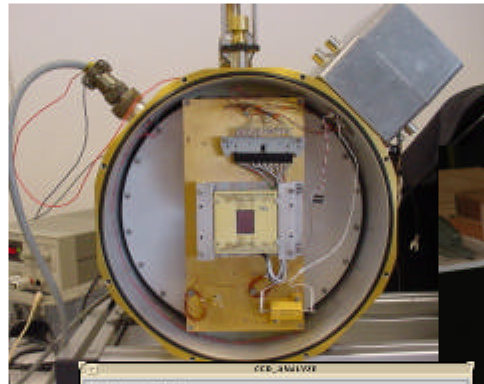
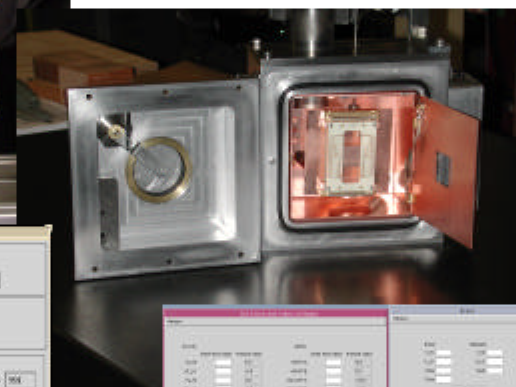
Chris Bebek
Lawrence Berkeley National Laboratory

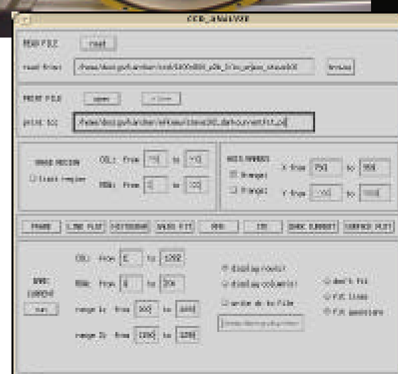
<u>Testing team</u>
John Bercovitz
Brenda Frye
Armin Karcher
Bill Kolbe
Bojan Turko
Joong Lee
Michela Uslenghi
Summer students

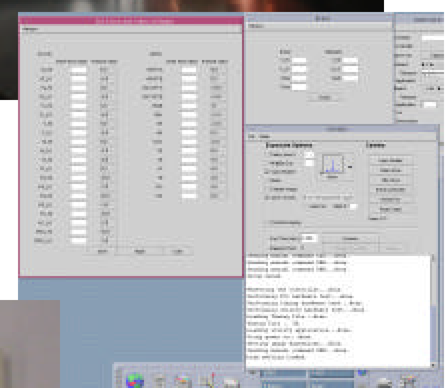
Test Facilities

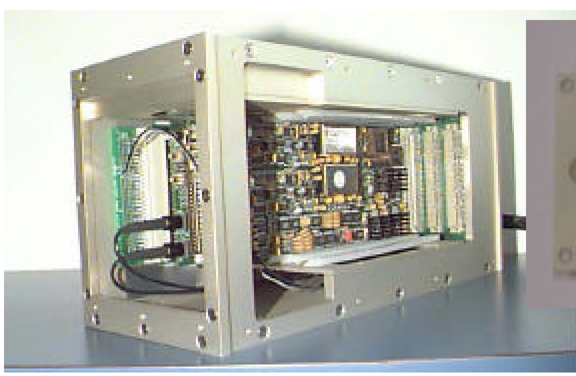
- 3 dewars
- 2 Leach readout controllers
  +1 on order
- 3 SUN workstations
- PC with CD-RW for archiving
- Vacuum furnace
- -40C refrigerator
- Class 10000 clean room
- Wire-bonder

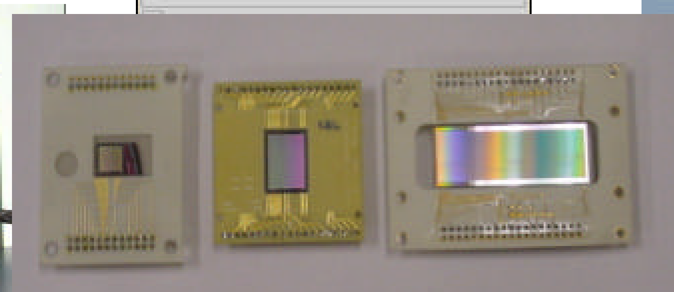






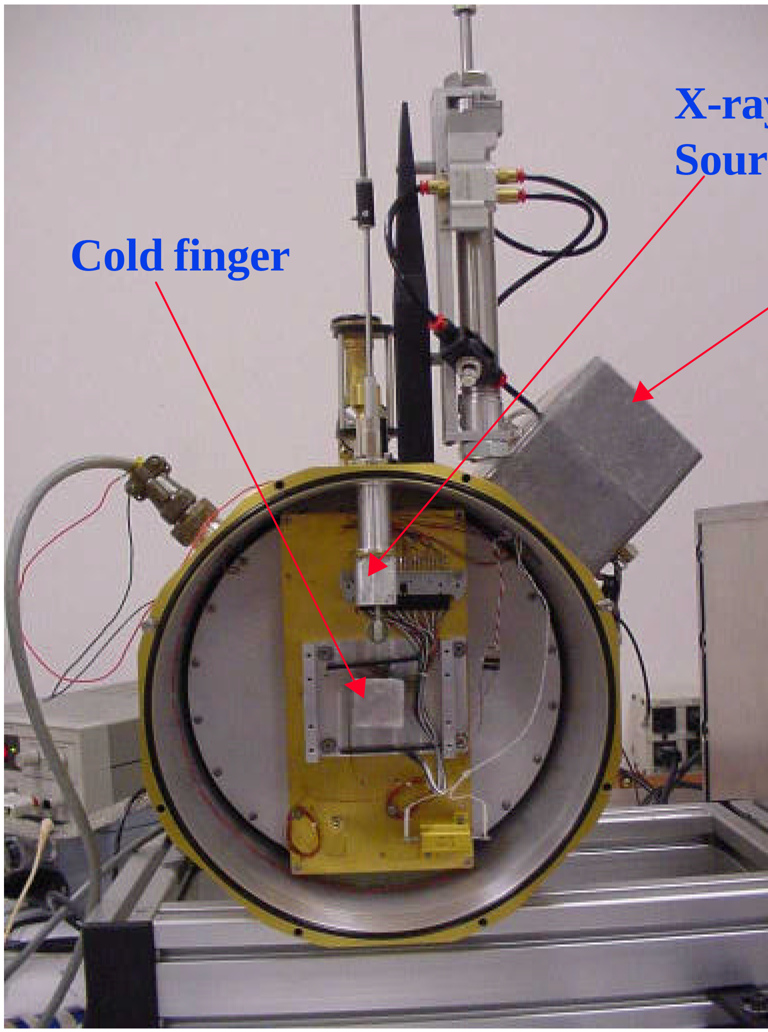


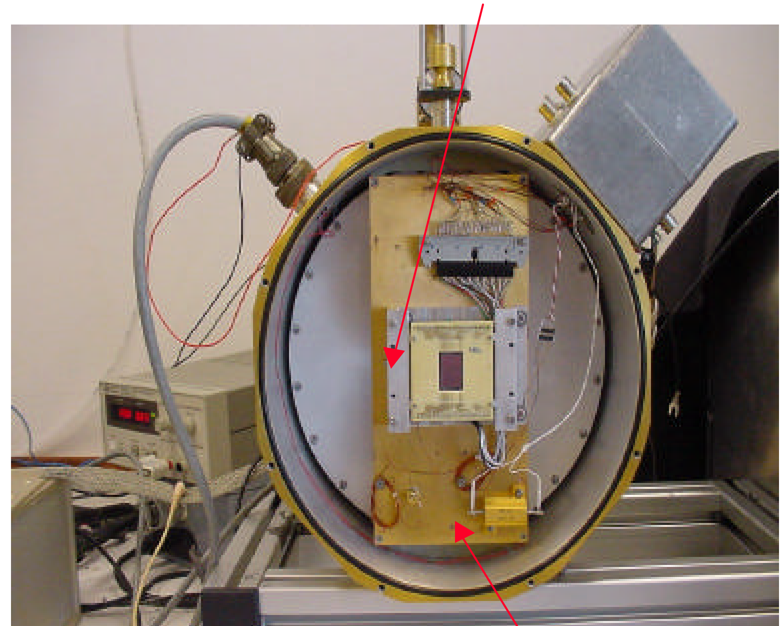




IR Labs Dewar

CCDs are operated at a nominal 150 K to make dark current small.
We use LN_2, a thermal switch, and a cold finger pressing against a face of the CCD (typically mounted on an AlN wafer).



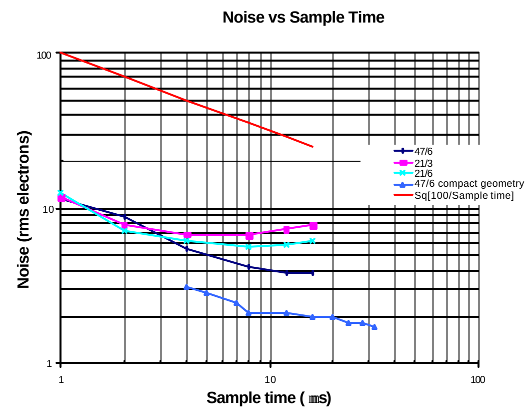


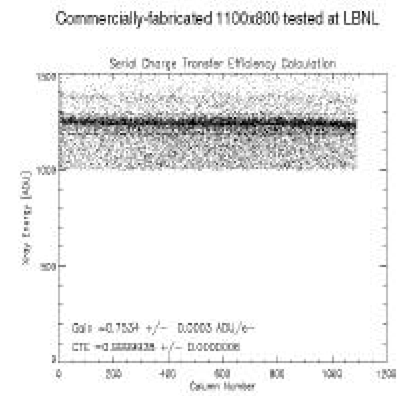
Non-optical Measurements

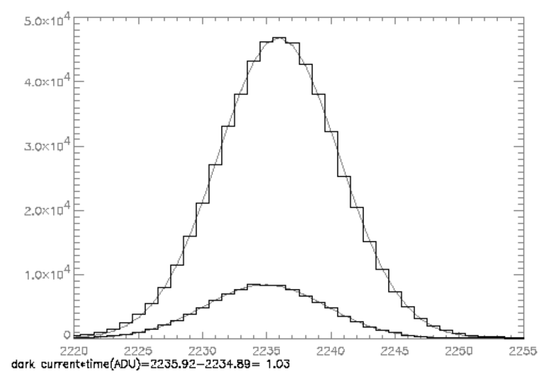
Read noise - impacts S/N especially when co-adding exposures.

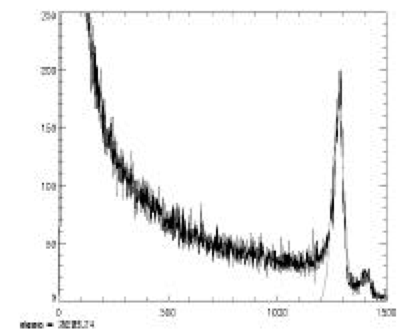
Dark current
- impacts exposure times.

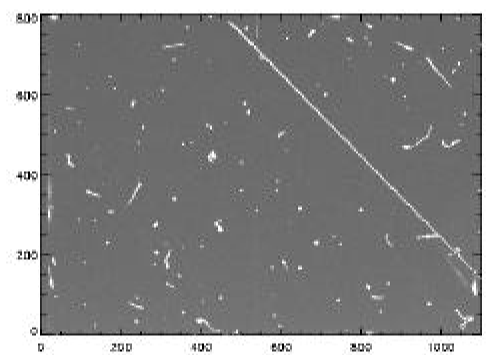
Charge Transfer Efficiency
- x-y calibration of signal loss.

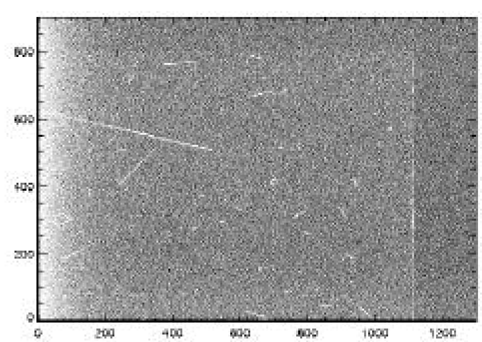


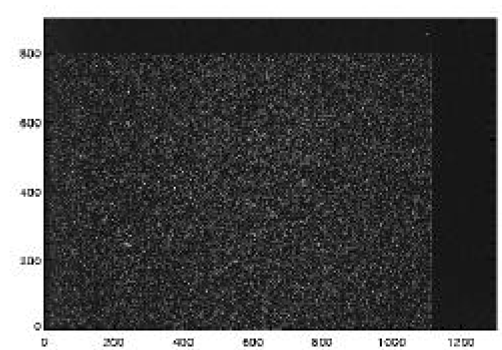






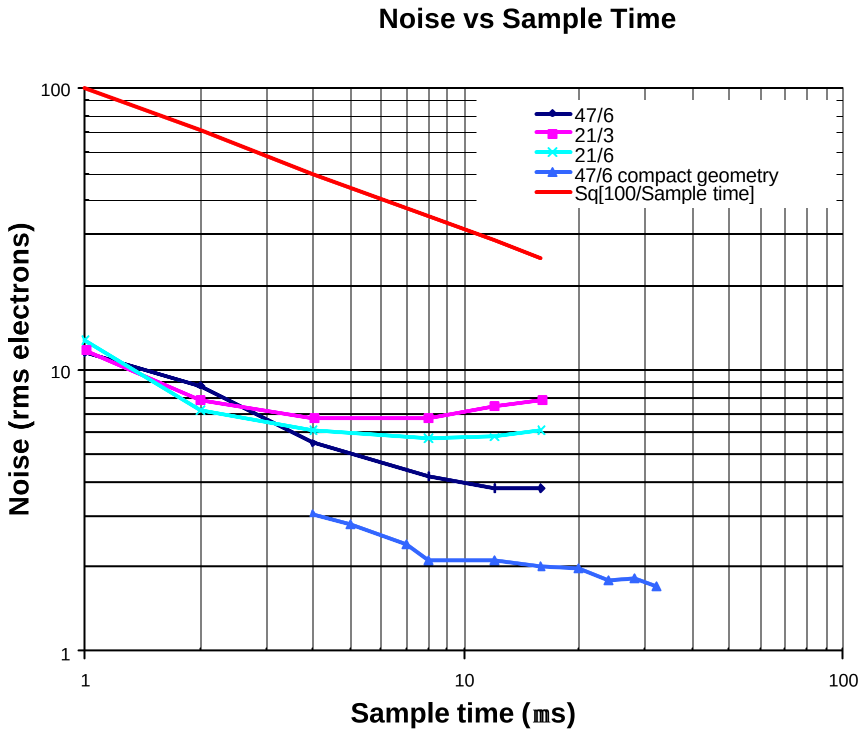






Read Noise Measurements (covered by Steve)

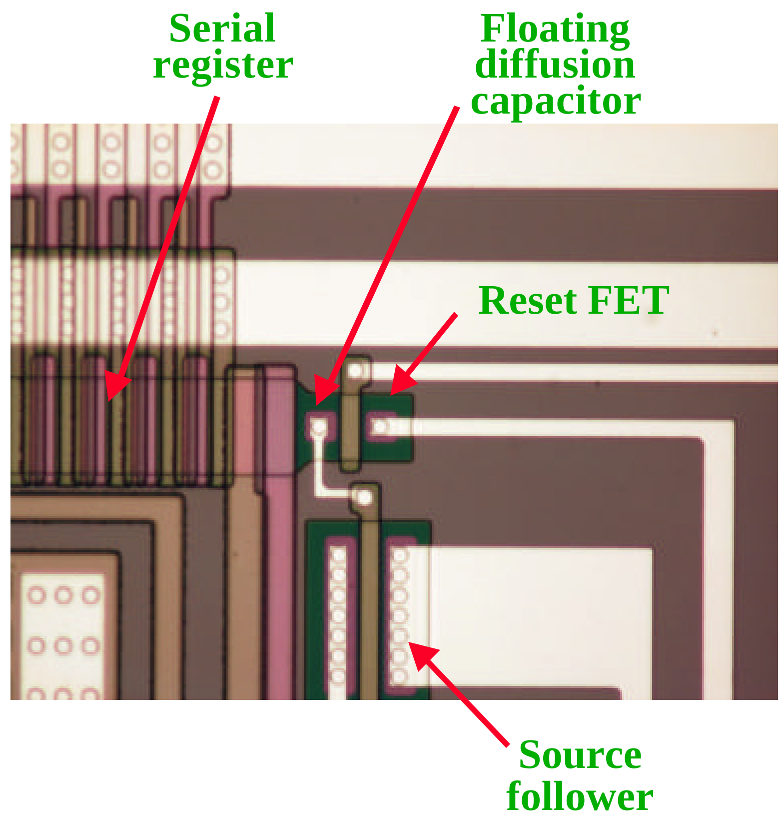
Noise after correlated double sampling.

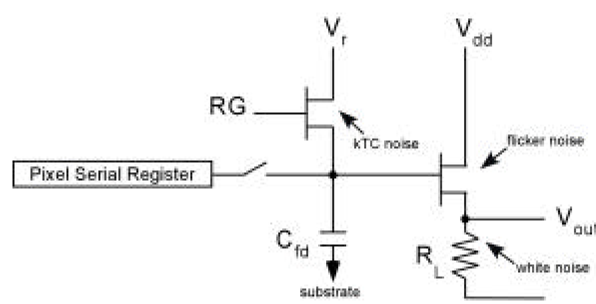


Sample time is the width of the reset or video integration.

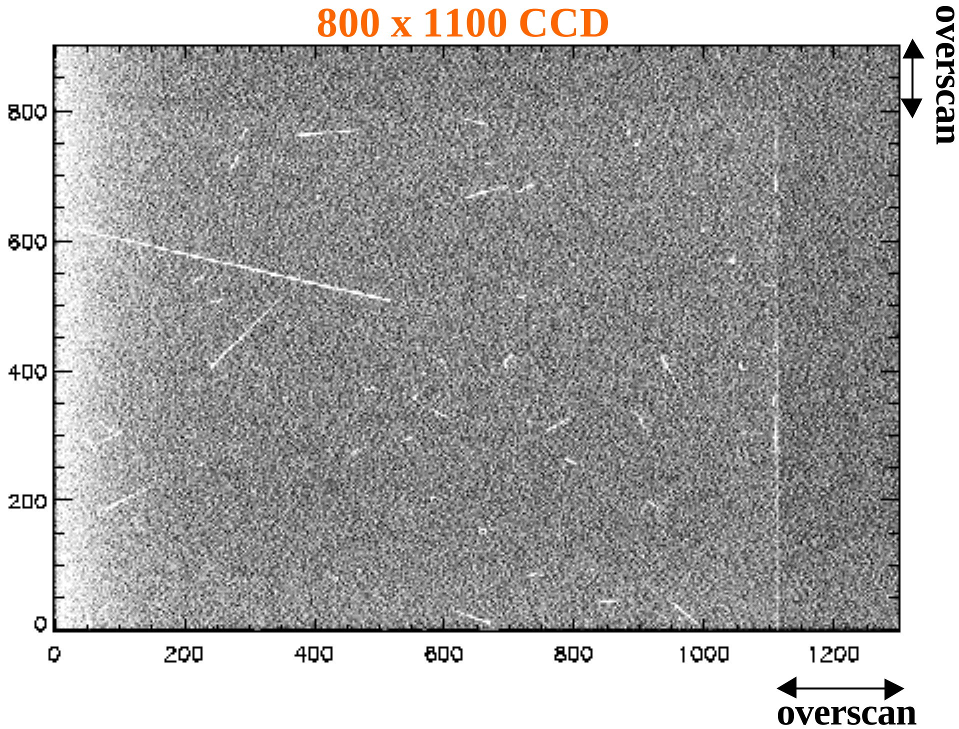
Measurements courtesy of Lick/UCSC.

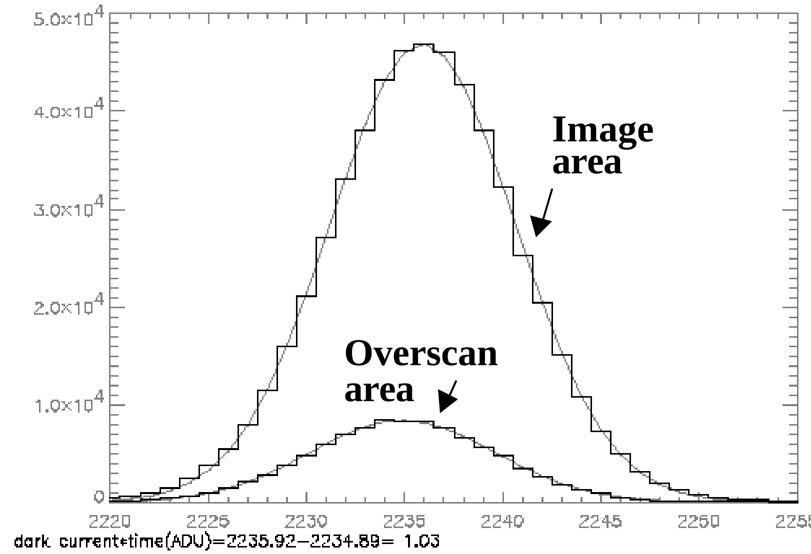
Low capacitance readout geometry.
Read noise of 2e and sensitivity of 6 mV/e.

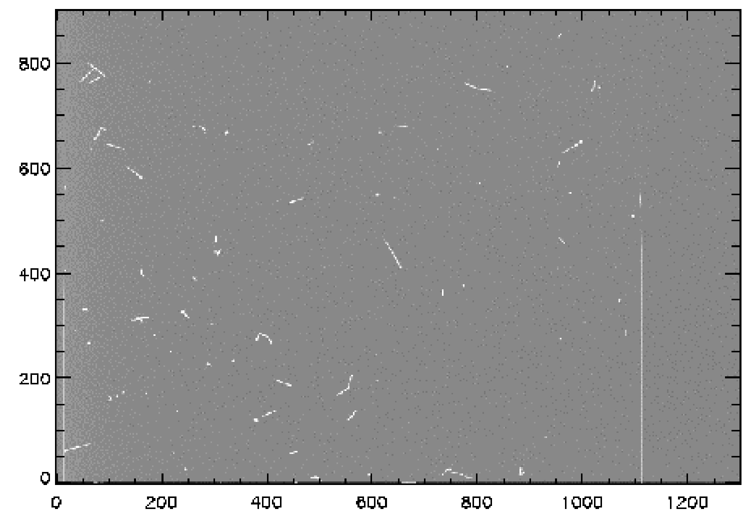




Dark Current Measurement







Measured dark current per 1000 sec obtained by fitting image area and overscan areas and subtracting gaussian peaks.

Dark charge collected = 0.0025 e-/s or 9.0 e-/pixel/hour.

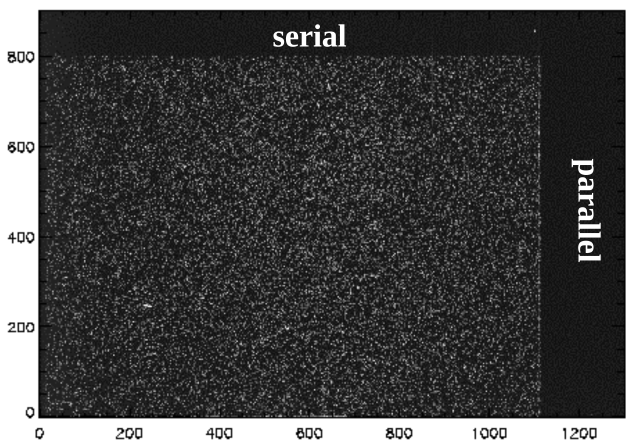
CTE Measurements

For every pixel to pixel charge transfer there is the potential for some charge loss.
CTI is the charge transfer inefficiency.
CTE is the complement.

A CTI or CTE is quoted for both the serial and parallel transfers.

We use the Mn Kα x-ray line of ^{55}Fe as a known deposition of 1620 electrons.
We see how well 1620 electrons is reconstructed as a function of position in the CCD.

LBNL CTIs of 5 x10^{-6} are typical (pre-radiation).



CTI = 1 - CTE

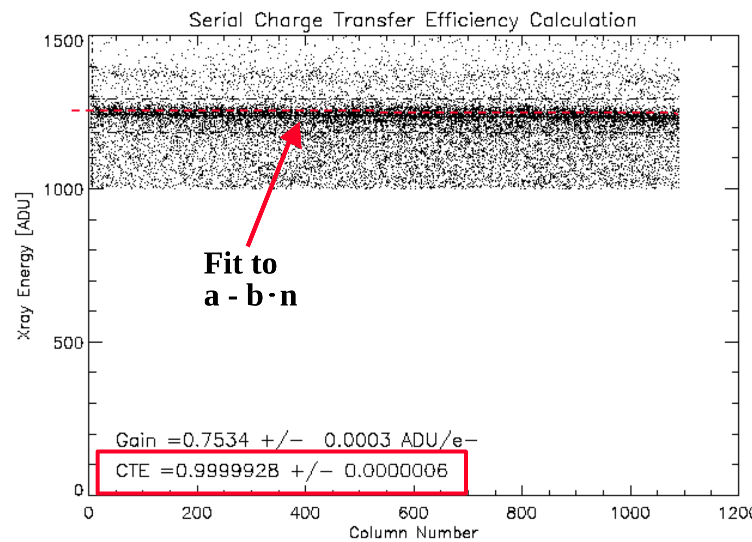
$CTI^n = (Q_1 - Q_n)/n = b*n/a$

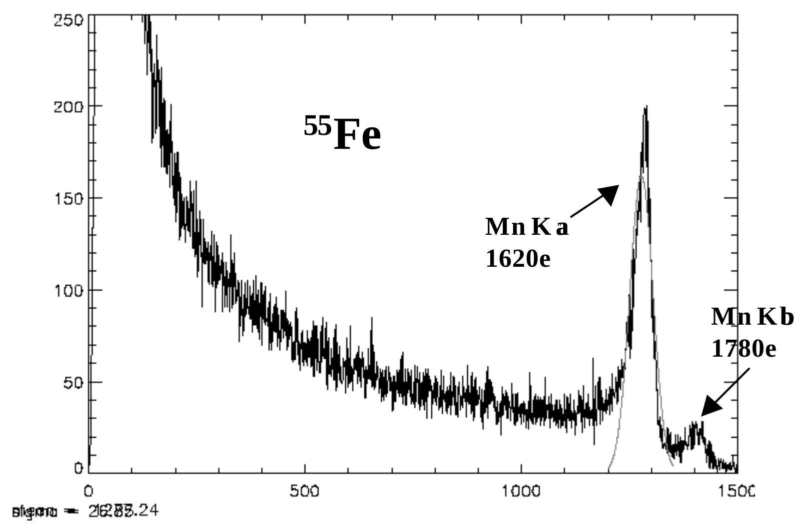
CTI = b/a for b/a<<1

(n is the number of rows or columns)

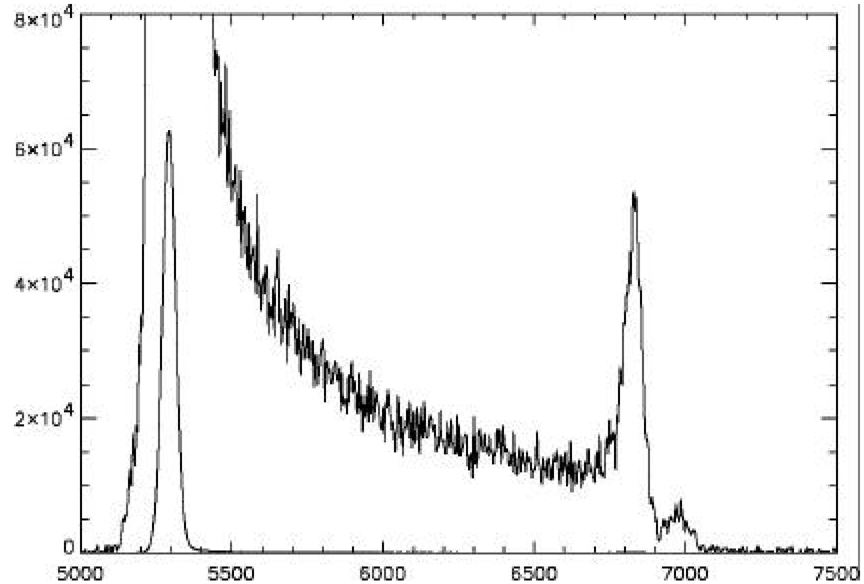
note

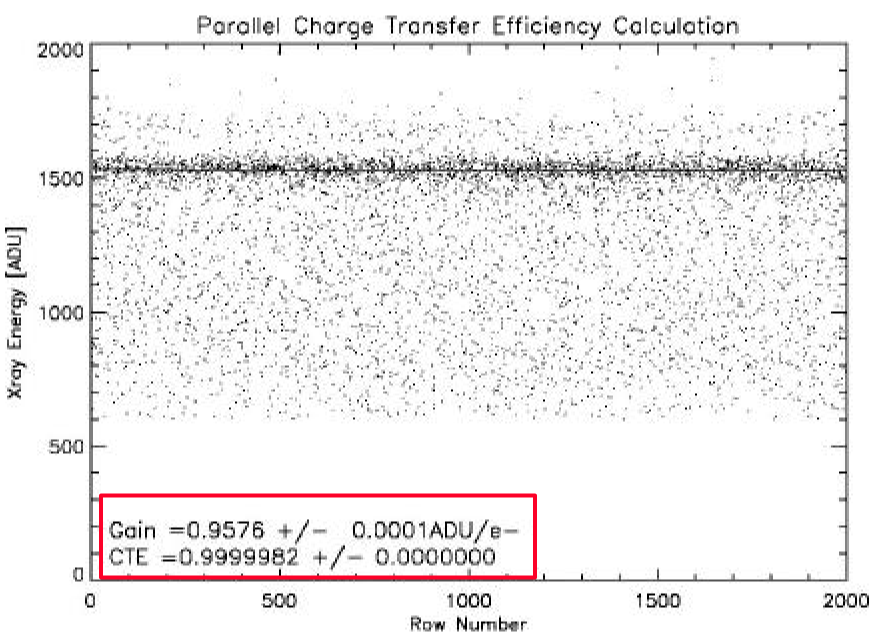
Commercially-fabricated 1100x800 tested at LBNL

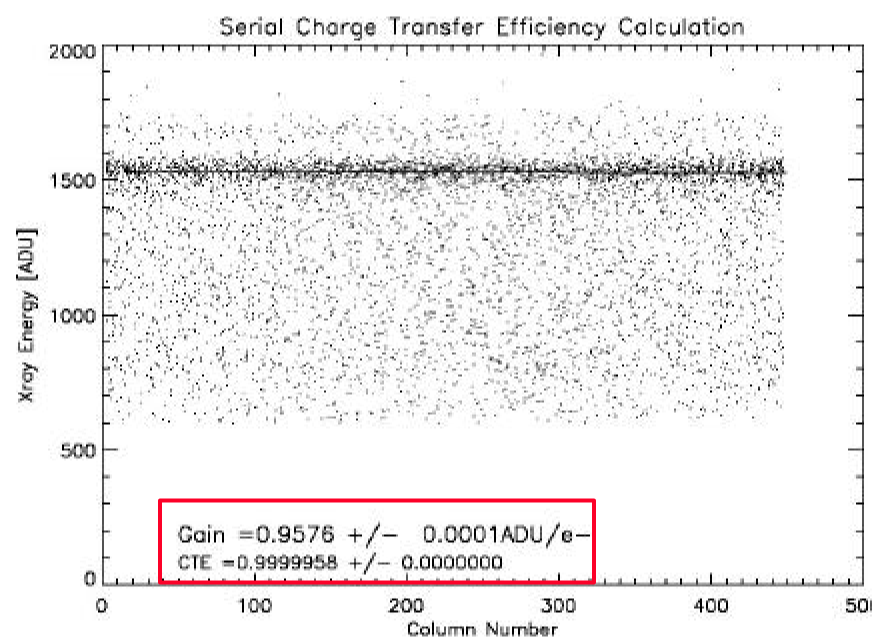




CTE - 12 mm device



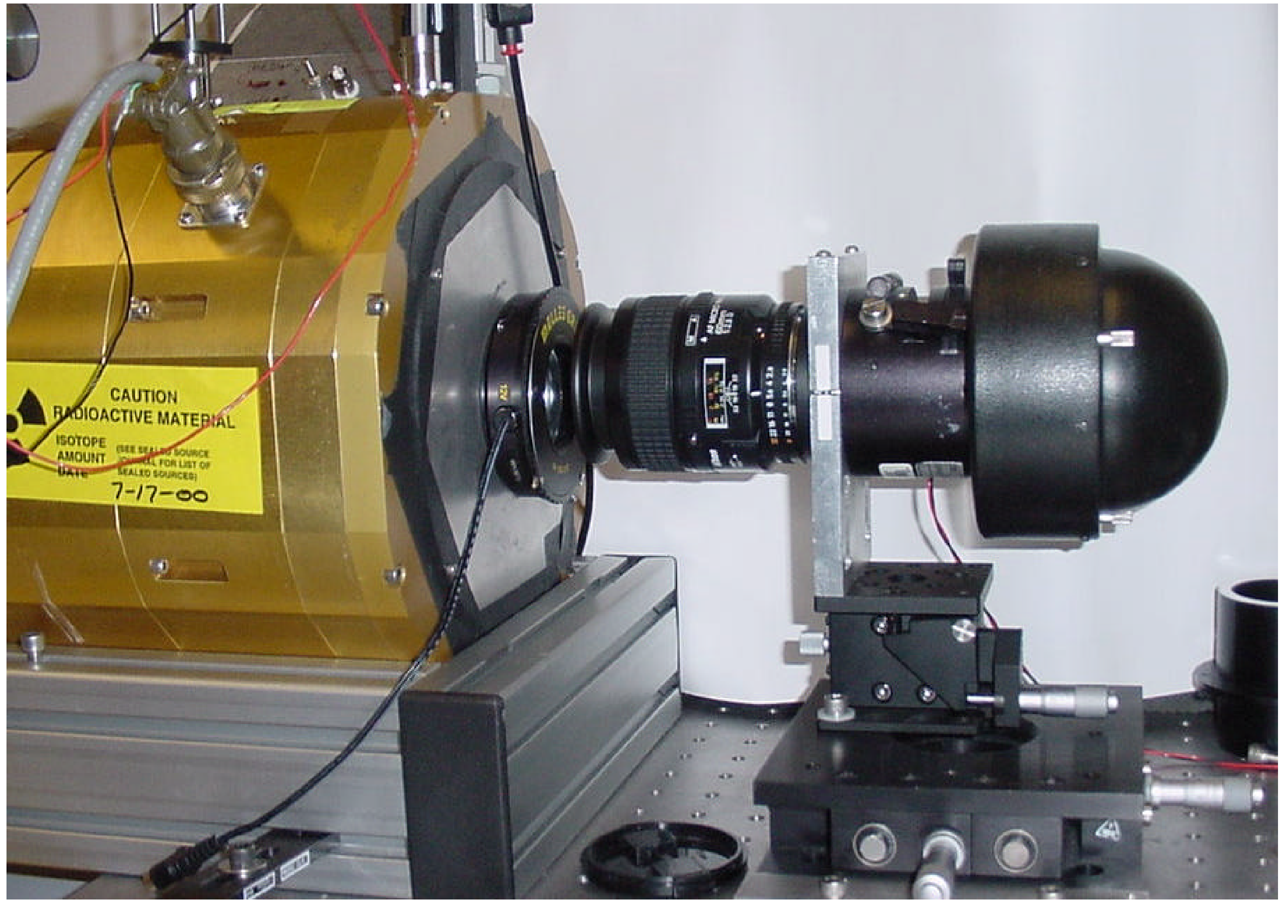




Optical Measurements

Present abilities
- Linearity
- Well depth
- Erasure

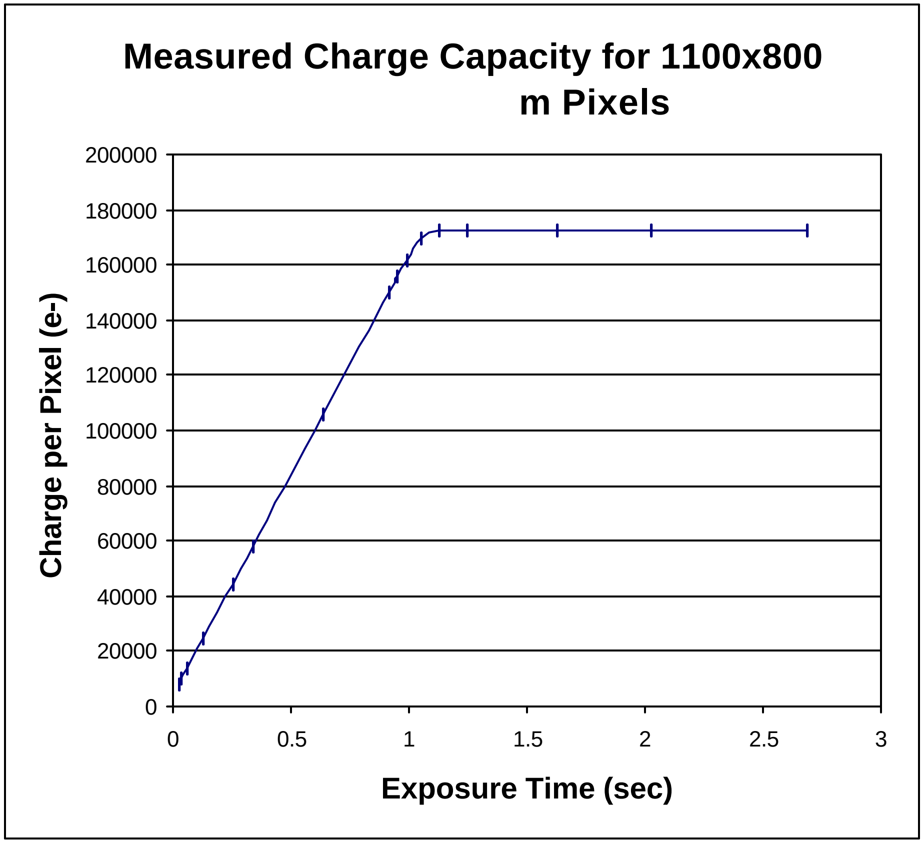
Need to develop
- CTE *vs* charge
- QE
- MTF
- Trap density
- Cross talk



View showing dewar with attached shutter and Optoliner projector fitted with Nikon macro lens and xyz stage.

Linearity and Well Depth

- Saturation curve obtained by plotting peak projected spot intensity versus exposure time.
- Full-well capacity in electrons obtained by scaling ADU's by CCD gain.
- 15 mm pixels
  - Well depth about 170 ke
  - Linearity is about 0.3%.
- Well depth is a function of pixel size. Preliminary 12 m m well depth found to be 150 ke.

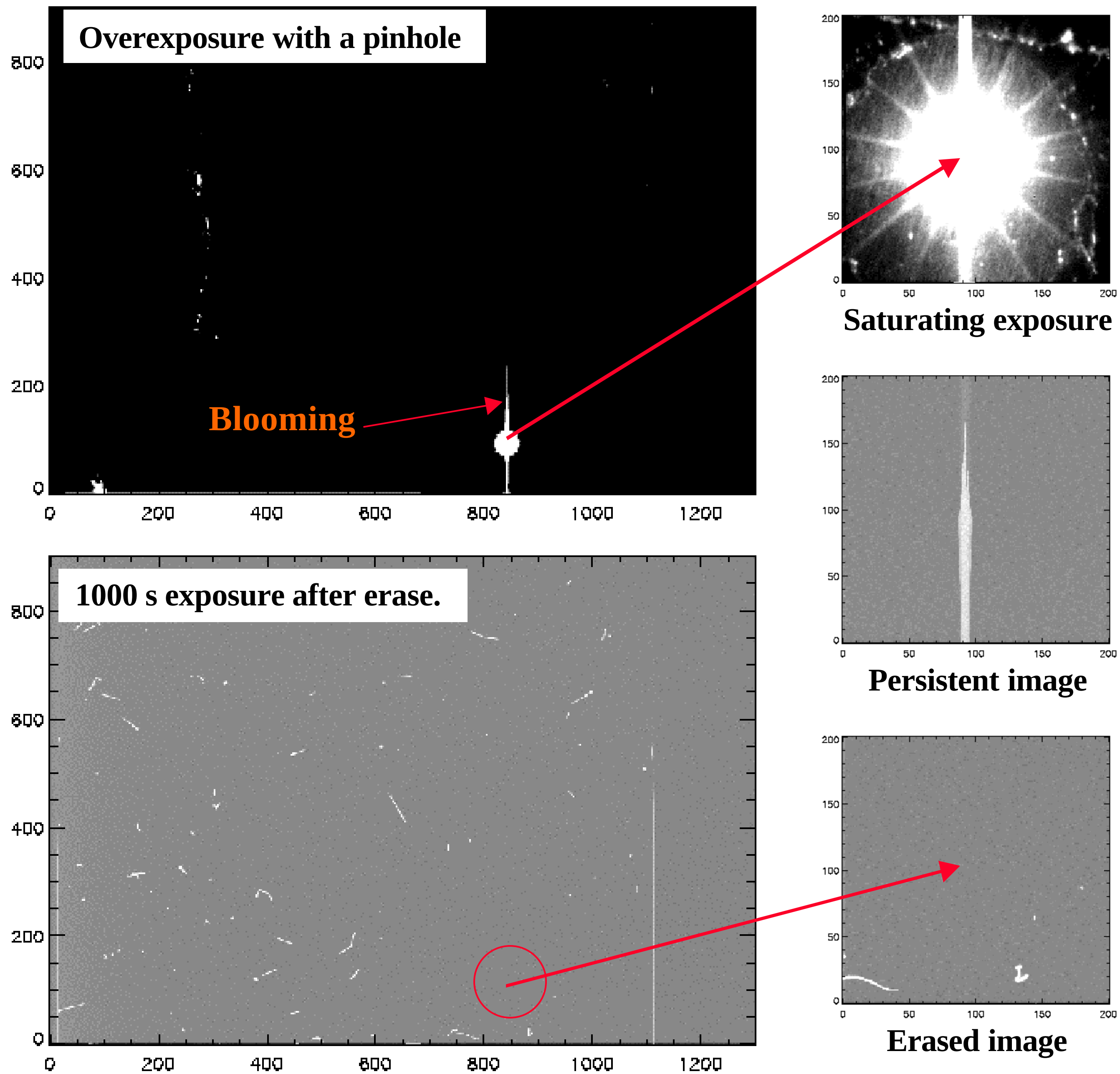


Persistent Images

Saturated images can persist for hours.

We have an effective erasing technique — flood channels with electrons.

NB. We observe our lowest dark currents after an erase cycle.

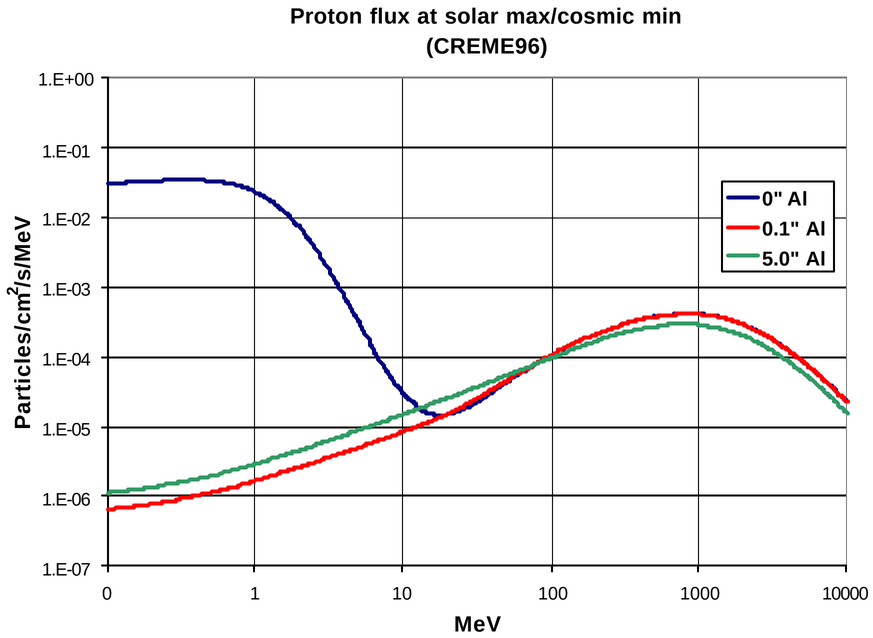


Radiation Damage

Space particle backgrounds have two components
- **Solar protons — sub-100 MeV**
- **Galactic cosmic rays**
- **(we are ignoring electrons here)**

Solar protons are most damaging to CCDs.
- **WFPC2 on HST developed losses up to 40% across its CCD due to radiation damage.**
- **Hot pixels also developed.**

Some shielding makes a big impact.



Radiation testing is done at the LBNL 88” Cyclotron with 12 MeV protons.

We measure pre- and post-radiation
- **FET I-V,**
- **FET sub-threshold curves,**
- **Dark current,**
- **Read noise,**
- **Serial and parallel CTE.**

Radiation Damage - Traps

CTI Using Shockley-Read-Hall Theory

$$CTI_{PIXEL} = \left(\frac{V_s}{N_s} * N_t\right)\left(\exp\left(-\frac{T_t}{t_e}\right)\right)\left(1 - \exp\left(-\frac{T_s}{t_e}\right)\right)$$

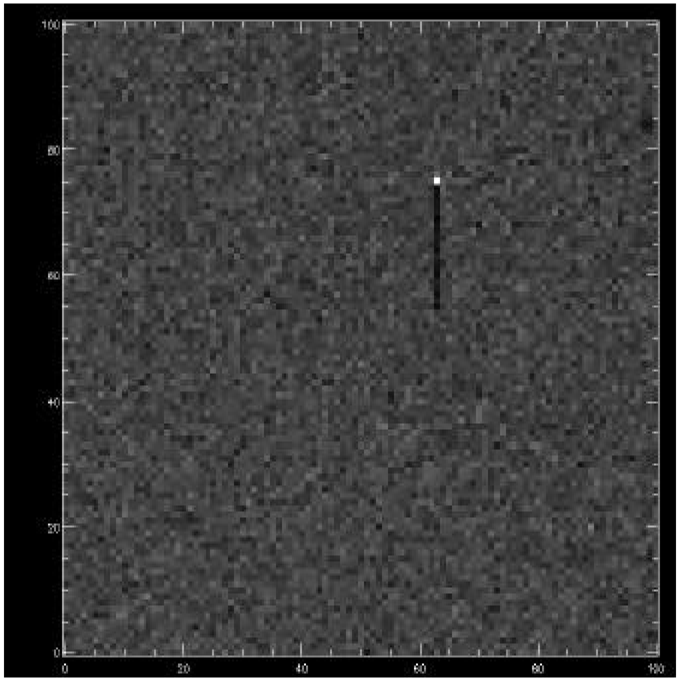
V_s = signal volume, N_s = # signal electrons, N_t = # traps,
T_t = clock period, T_s = time between x-ray events, t_e = trap emission time

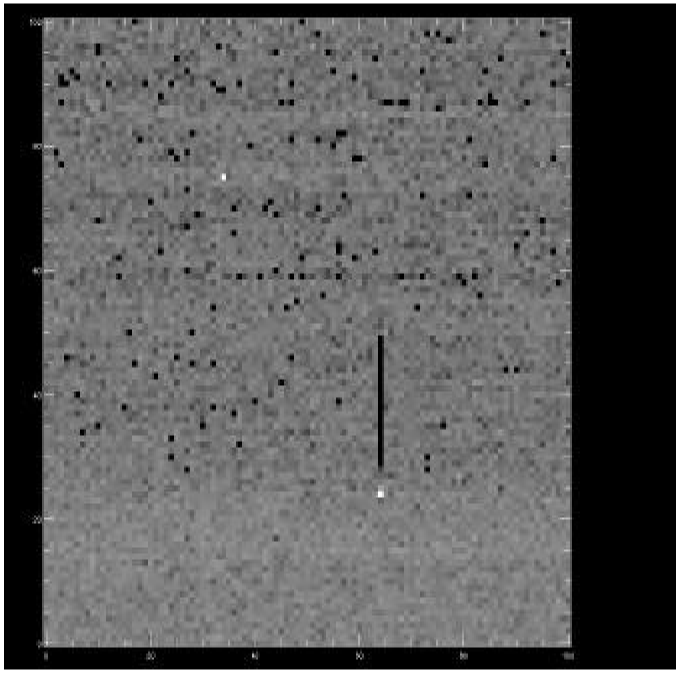
A Charge Packet Encounters An Empty Pixel ....

- # Trapped Charges Relative to Size of Charge Packet
- Probability a Charge Will Remain Trapped
- Probability a Charge Will Be Emitted Before the Next Packet Arrives & Trap will be Empty

Traps and Hot Pixels

Traps can be defects in the virgin silicon crystal.
They can be induced during wafer processing.
They can be generated by dislocation from radiation damage.





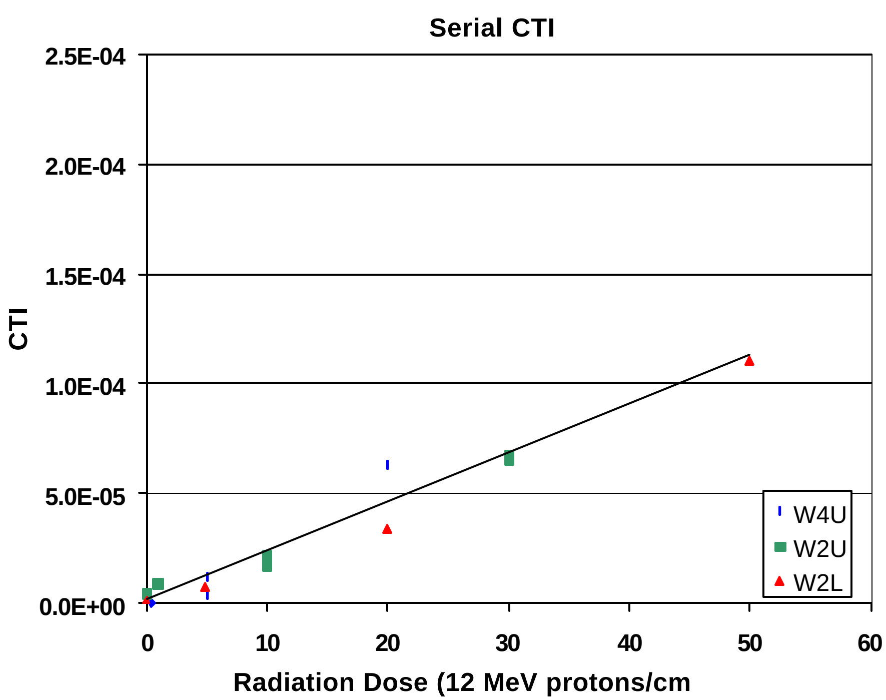
Pocket pumping - uniformly illuminate the CCD and then vibrate the image some number of cycles for some number of pixels.

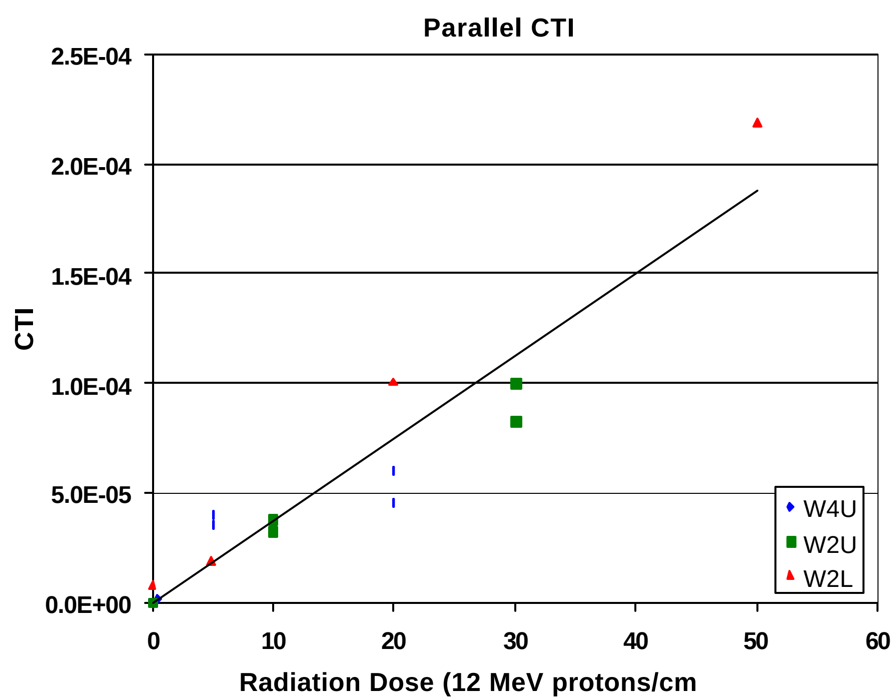
NB. Hot pixels leave a bright trail.

Radiation Damage - LBNL CCDs

12 MeV proton results from the 88” Cyclotron

CCD	Type	Radiation Dose (protons/cm^2)		
		1st dose	2nd dose	3rd dose
W4U	1100 x 800	0.5×10^9	5.0×10^9	10.0×10^9
W2U	1101 x 800	1.0×10^9	10.0×10^9	20.0×10^9
W2l	1102 x 800	5.0×10^9	20.0×10^9	50.0×10^9
M2U	1104 x 800	10.0×10^9		



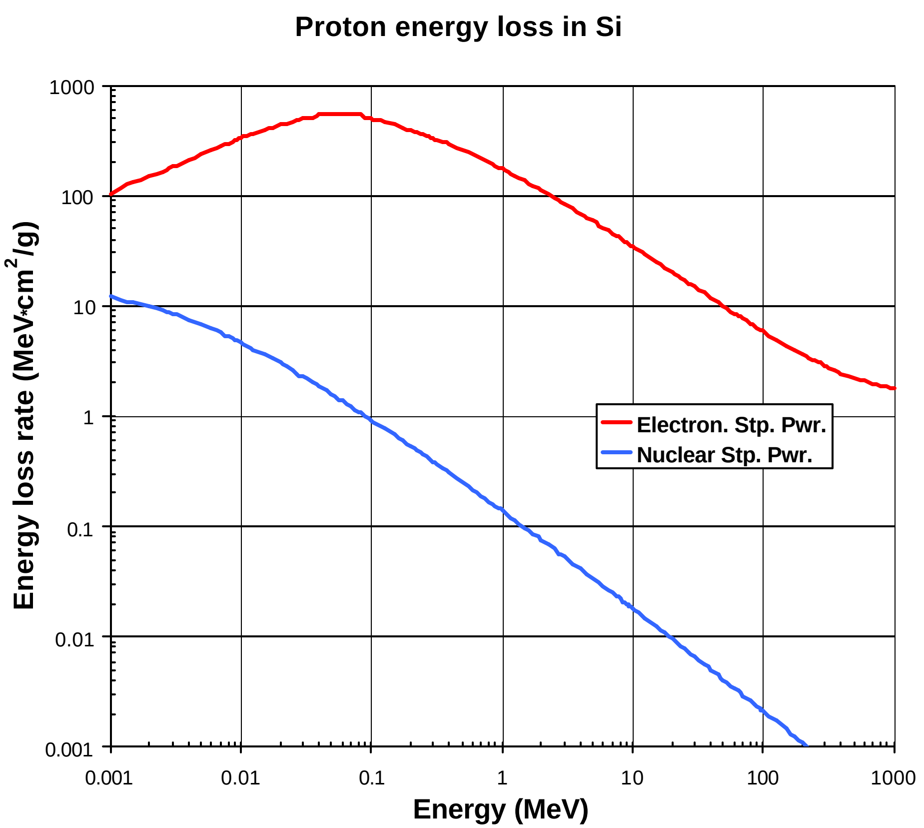


Radiation Damage

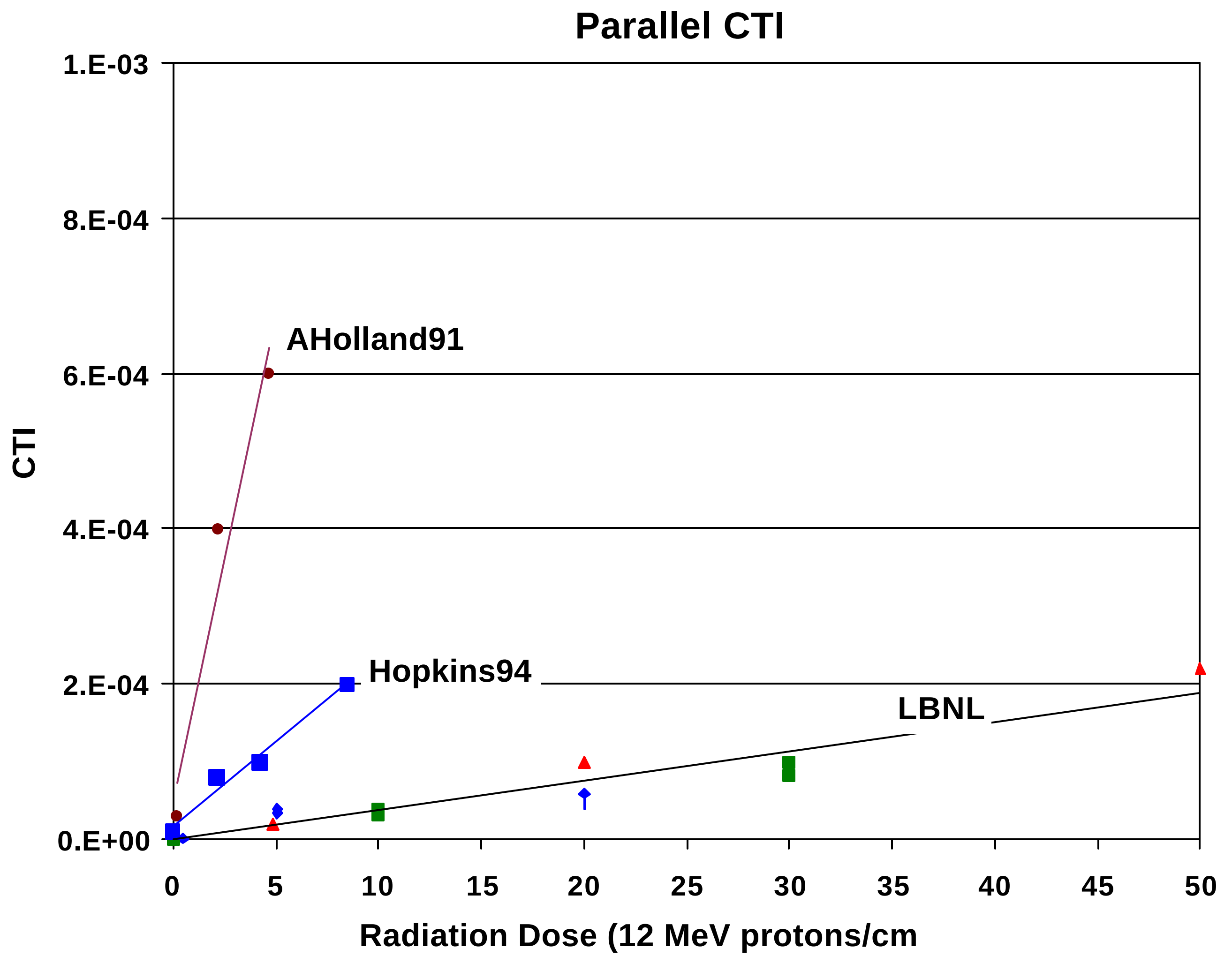
Measurements are not performed at the same energy or temperature.

The energy part can be corrected using the proton energy loss curve below.

Most damage is done by the NIEL component with integrated dosed quoted in MeV/g. For example, SNAP during 3 years of solar max flight gets 2 x 10^7 MeV/g, the equivalent of 10^9 12 MeV protons

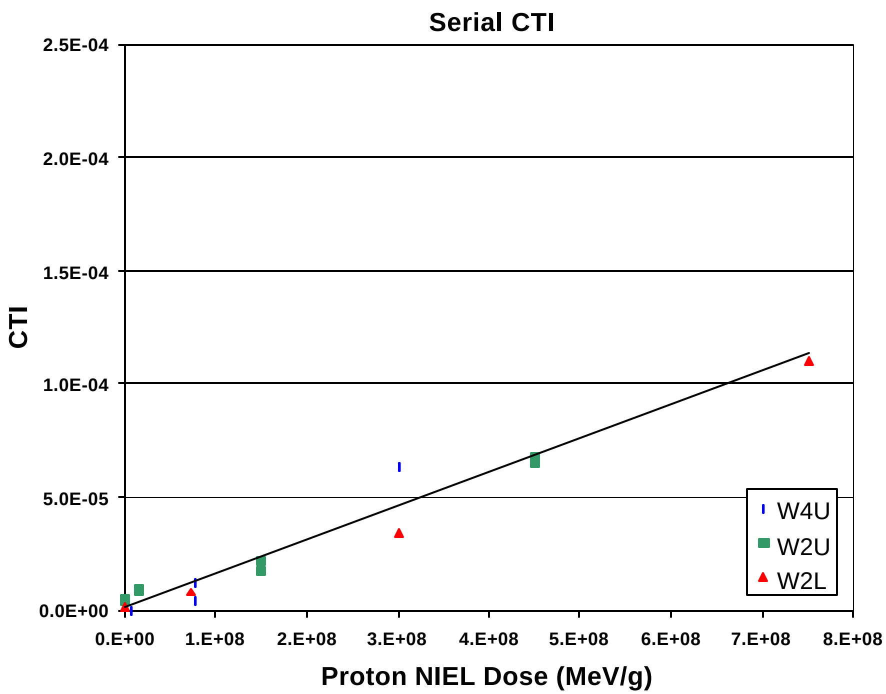


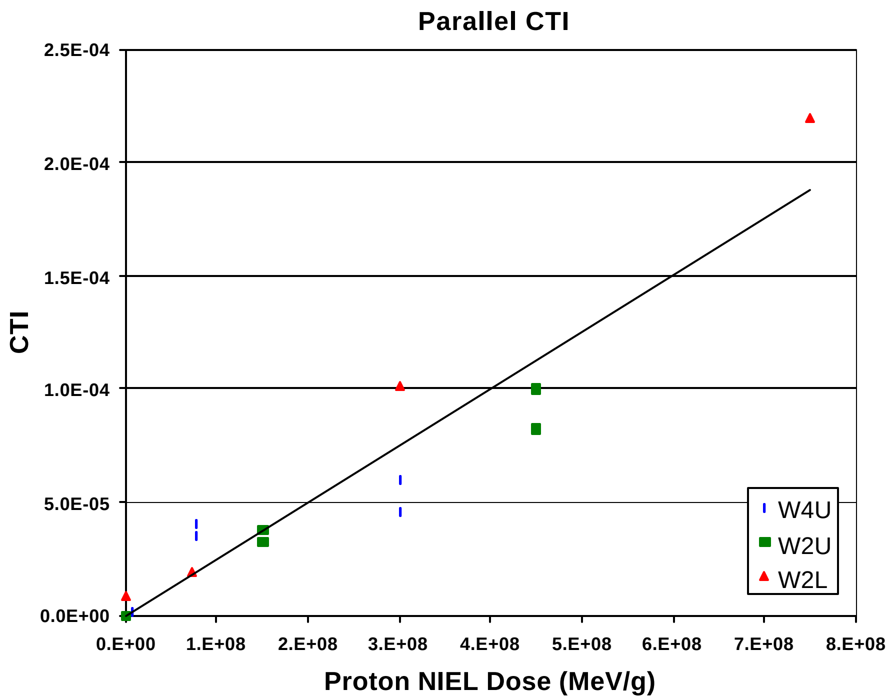
Radiation Damage



Radiation Damage - LBNL CCDs

CTI's replotted in terms of NIEL.





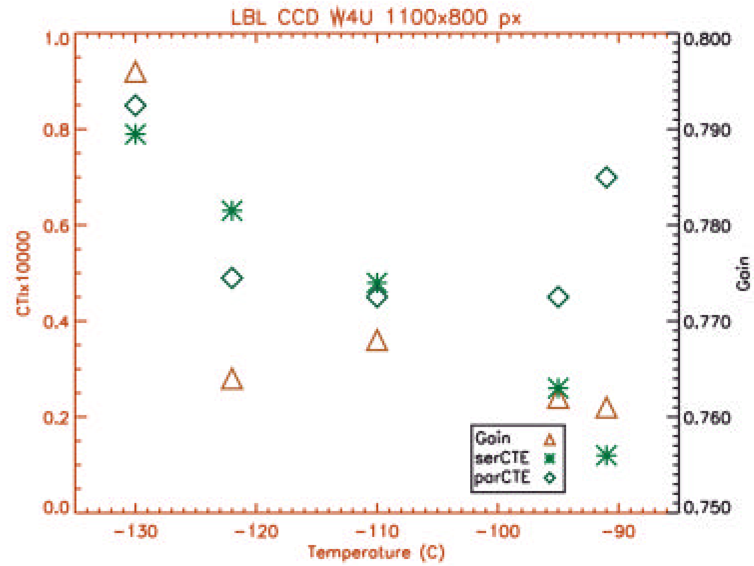
Why are is the parallel CTI worse than the serial CTI?

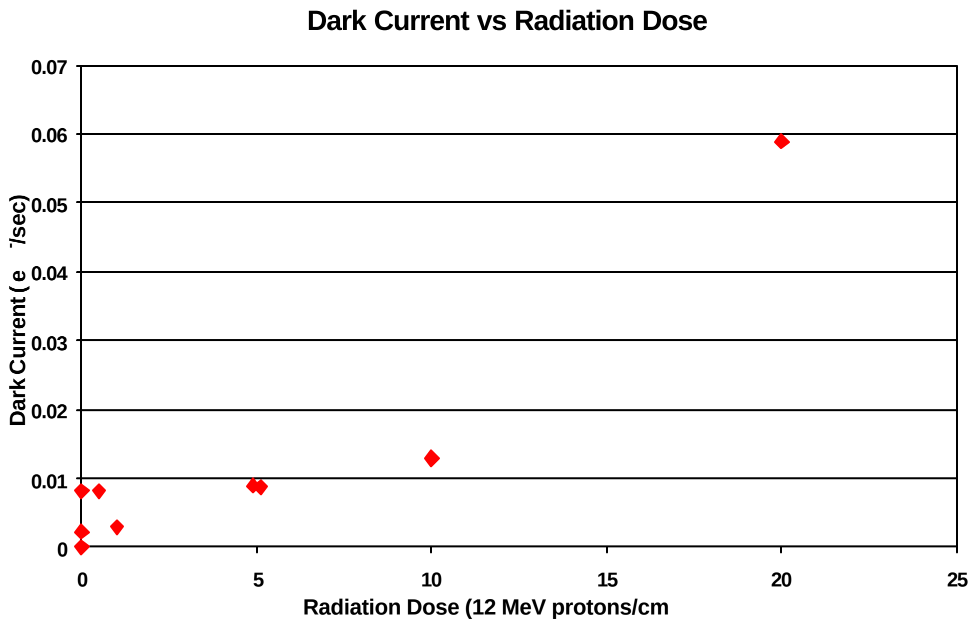
The serial channel has a notch implant to increase the charge density for small signals; the charge transport is therefore less sensitive to trap formation.

Where space permits, we are implementing a notch implant in the parallel channels in upcoming devices.

Radiation Damage - Future Work

- What's missing?
  - Dark current as a function of temperature and radiation dose.
  - Direct measurement of defects via pocket pumping.
  - CTI as a function of charge packet size.
  - Ionizing dose damage.
  - Dosing while cold and powered.
  - Annealing.





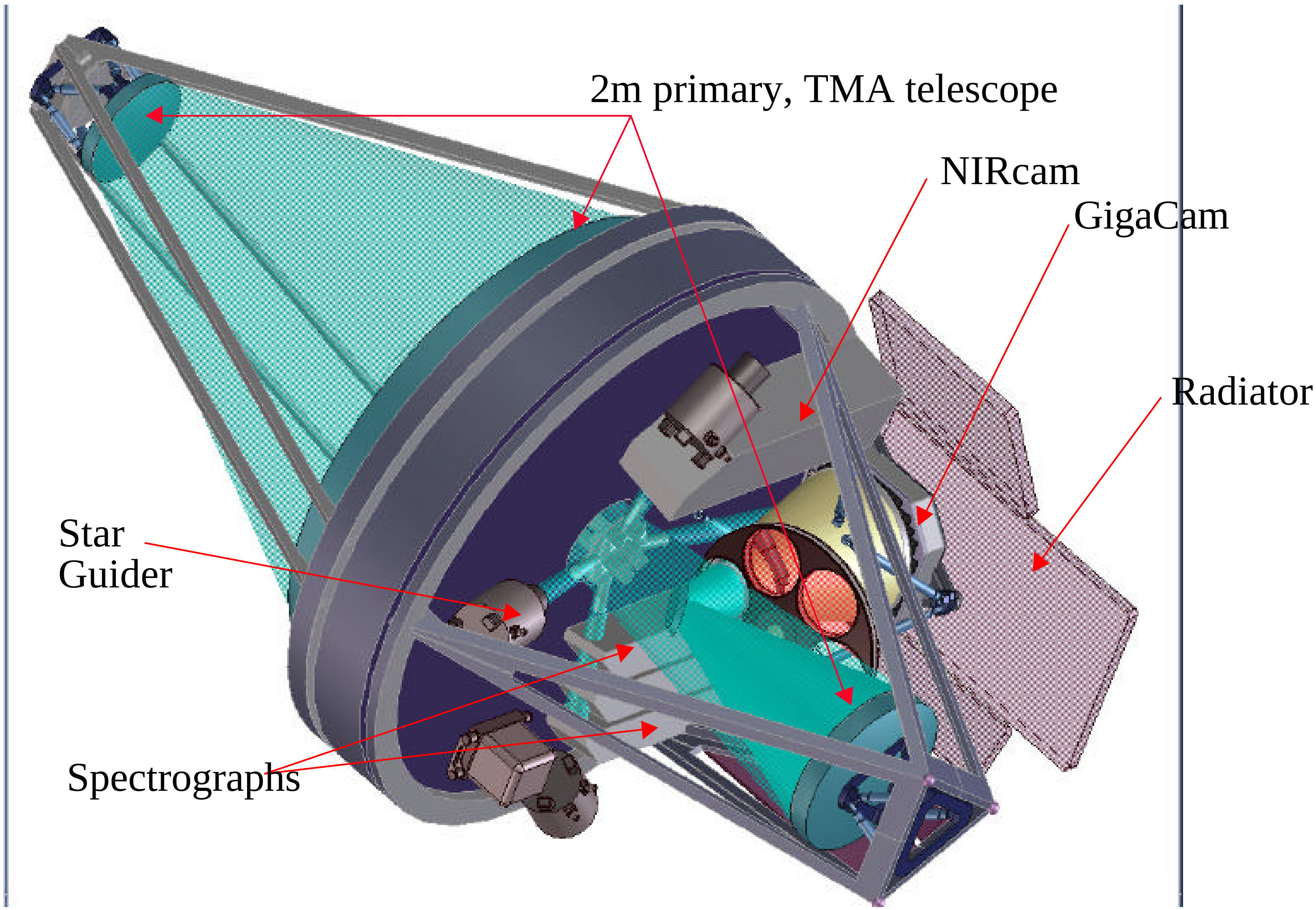
Testing Conclusions

High-resistivity results:

- **Low read noise is achievable on high resistivity silicon.**
- **Low dark currents are also achievable.**
- **Initial CTEs are very good.**
- **CTEs are robust to proton radiation damage.**

SuperNova Acceleration/Probe

Another potential customer for LBNL CCDs.



Optical Imager - GigaCam

Goals for optical imager:

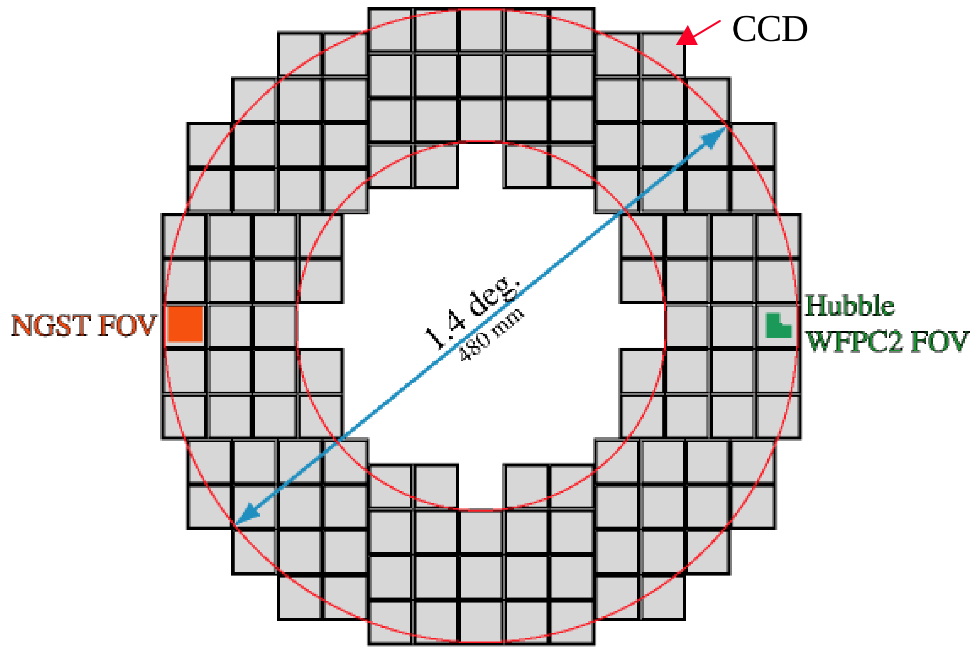
Populate 1° x 1° focal plane with small dead space.

Broad spectral response with high quantum efficiency.

Low read noise to allow stacking multiple exposures.

Low dark current to allow long exposures.

Stable performance in presence of >3 years radiation.



Moon

SNAP CCD Concept

~3 cm x 3 cm:

2 x 2860 x 1430 10.5 mm

or

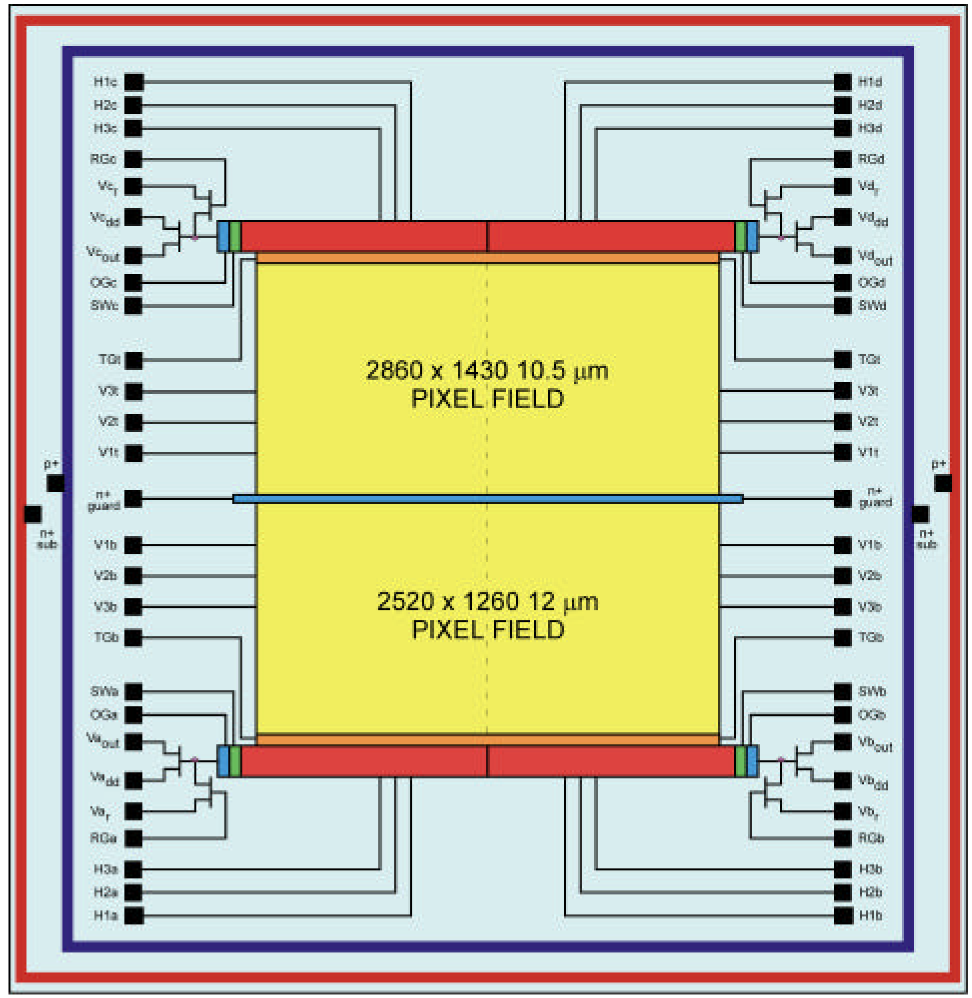
2 x 2520 x 1260 12.0 mm

4-corner readout

- **short charge shift distance.**
- **short readout time.**

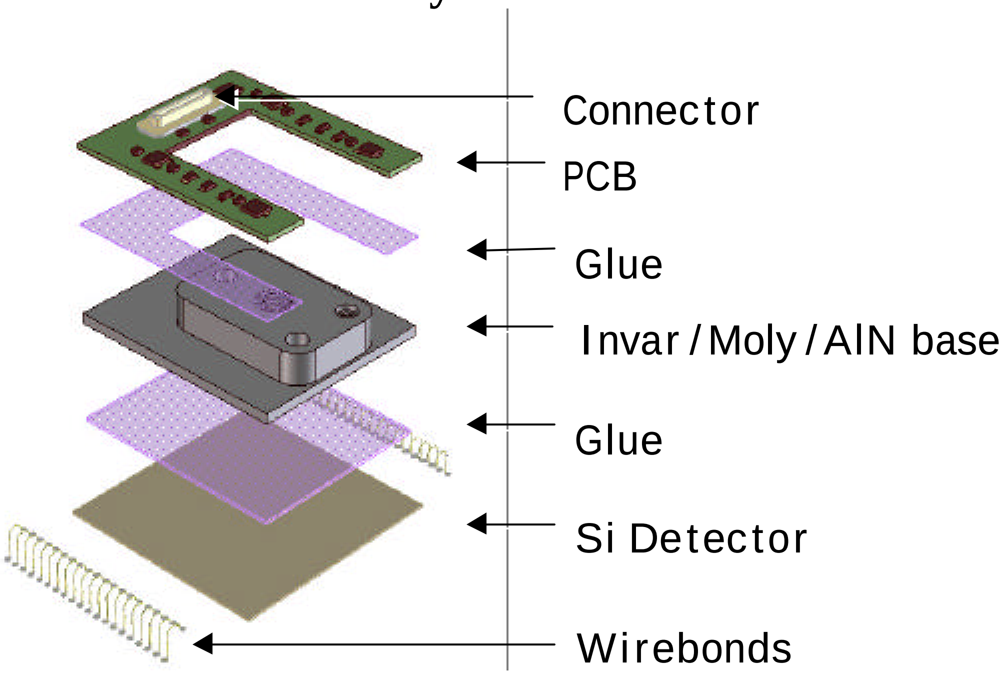
Read noise as low as 2 e.

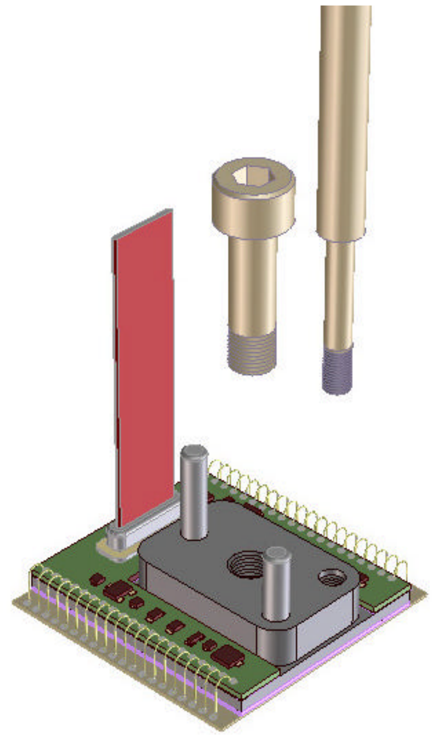
Sensitivity as high as 6 mV/e.



CCD Packaging

- Support CCD
- Connection to cold plate
- Four-side abuttabe for dense mosaic.
- Built-in mechanical precision – no shimming.
- Access to bonding pads
- Local electronics
- Cable connector
- Low mechanical stress in silicon from -150 C to +150 C.
- Low background radiation materials
- Low chemical reactivity with silicon





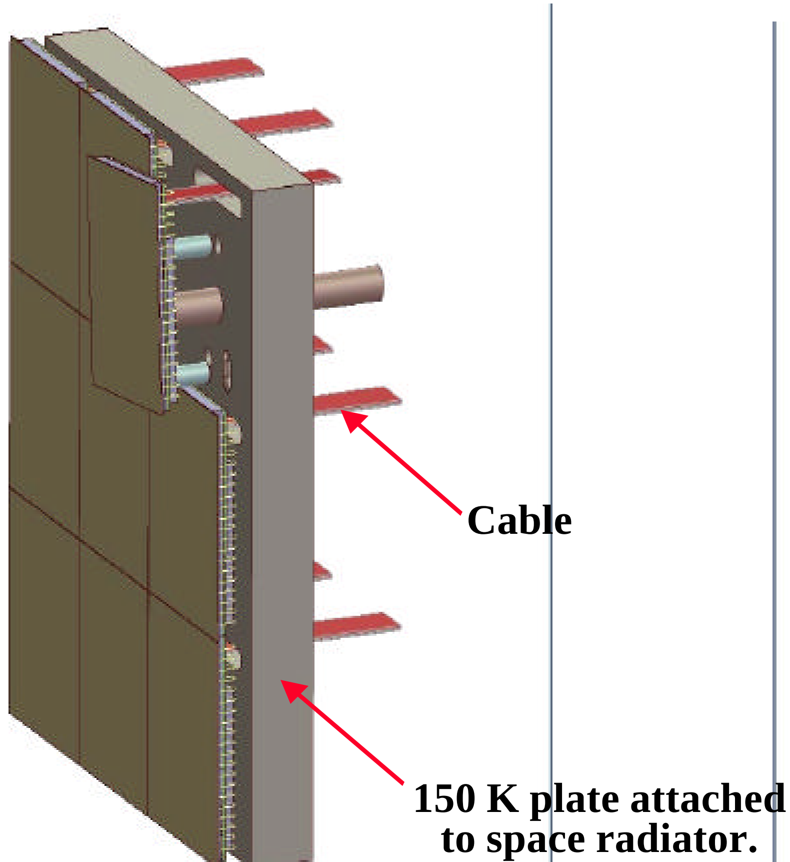
Mosaic Packaging

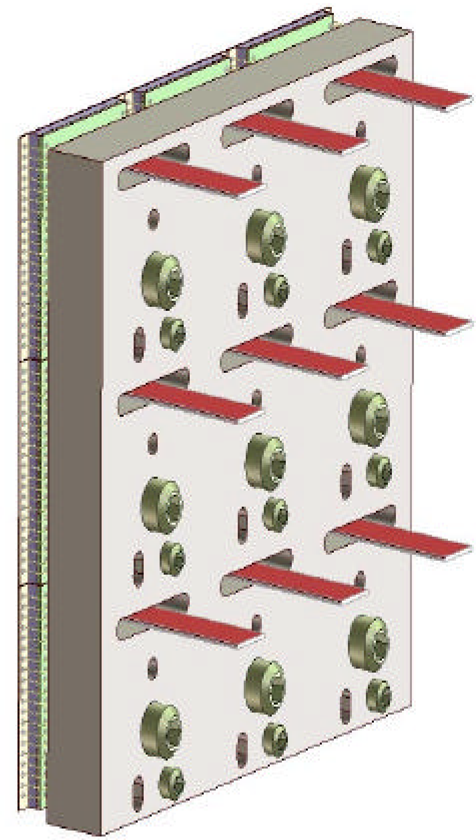
"Plug and play"

Precision CCD modules, precision baseplate, and adequate clearances designed in.

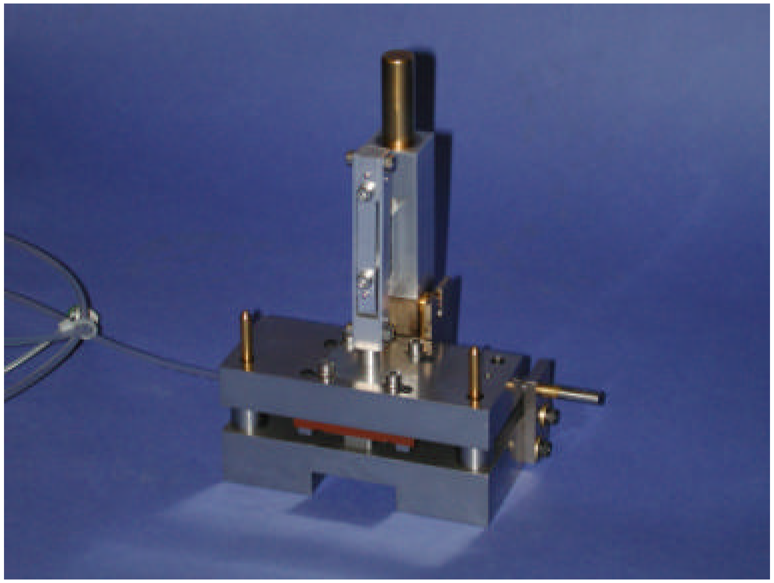
Focal plane tolerance is ±25 mm.

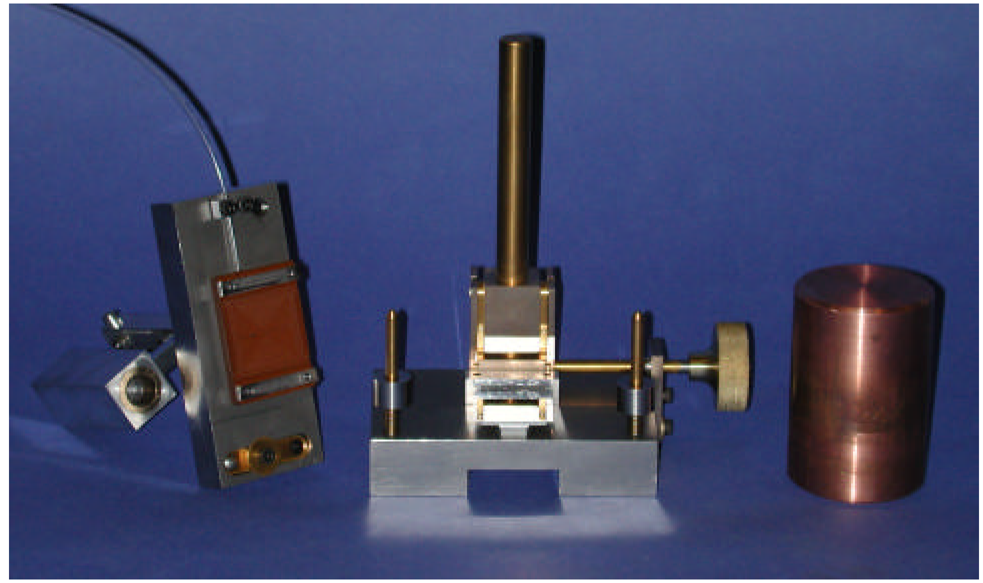
Final assembly can be *xyz* surveyed cold.





CCD Assembly





Alignment and gluing assembly fixture

- **Works for devices as large as 2k x 4k, 15 mm.**
- **Vacuum chuck can go into 150 C oven, if req'd.**
- **Vacuum chuck fits under wire-bonder head.**

Class 10000 cleanroom

- **Laminar flow bench**
- **Wire-bonder**

Readout Electronics

Readout electronics

- **GigaCam — 150–250 CCDs.**
- **W/NIRcam — 1–24 HgCdTe devices.**
- **Spectrographs — 4 devices, 2 CCDs and 2 HgCdTe.**
- **Low power and small space highly desirable in a satellite.**
- **Judicious use of ASICs where most benefit is derived.**

DAQ

- **Collect data streams, compress, and buffer.**
- **Transmit all data to ground.**

Instrument Controls

- **Electronics configuration parameters: modes, voltage levels, *etc.***
- **Mechanisms that need to be cycled.**
- **Instruments monitoring information.**

Readout Electronics Concept

•**CDS** – Correlated Double Samples is used for readout of the CCDs to achieve the required readout noise. Programmable gain receiver, dual-ramp architecture, and ADC buffer. HgCdTe compatible.

•**ADC** – 16-bit, 100 kHz equivalent conversion rate per CCD (could be a single muxed 400 kHz unit).

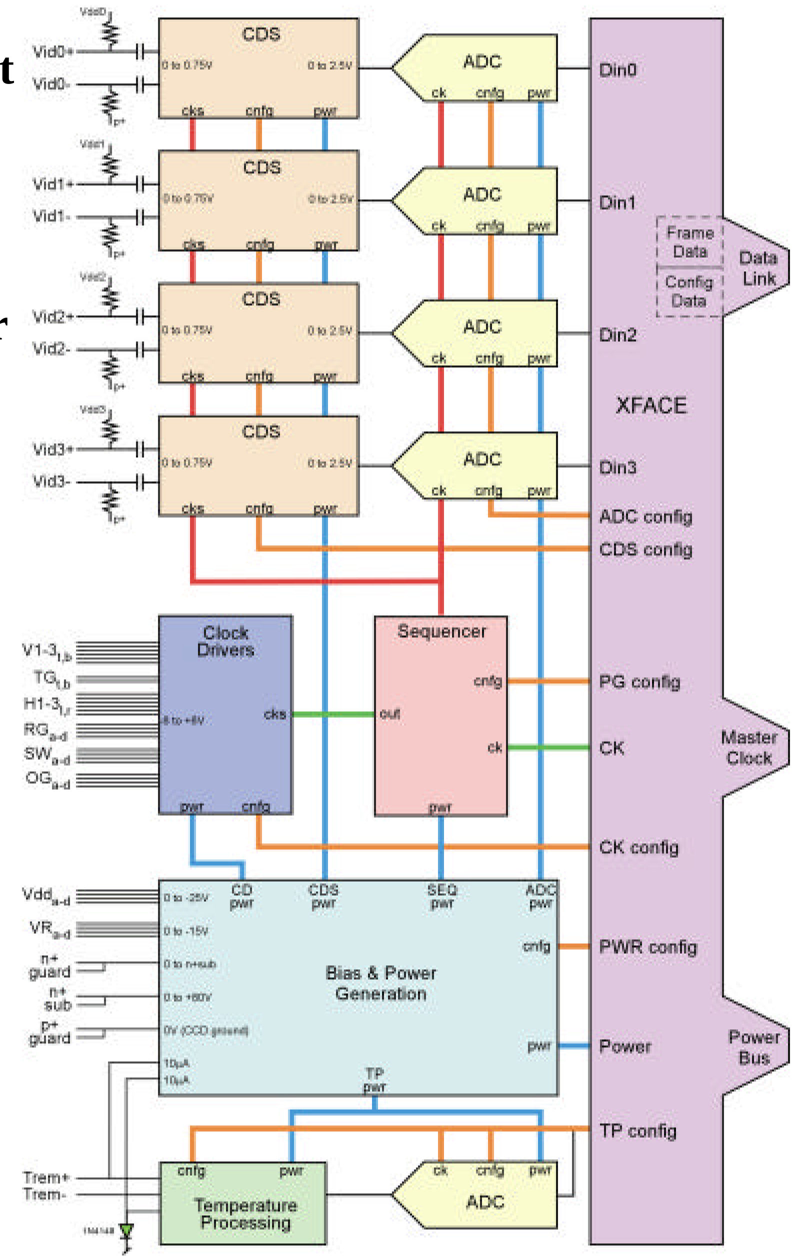
•**Sequencer** – Clock pattern generator supporting modes of operation: erase, expose, readout, idle.

•**Clock drivers** – Programmable amplitude and rise/fall times. Supports 4-corner or 2-corner readout.

•**Bias and power generation** – Provide switched, programmable large voltages for CCD and local power.

•**Temperature monitoring** – Local and remote.

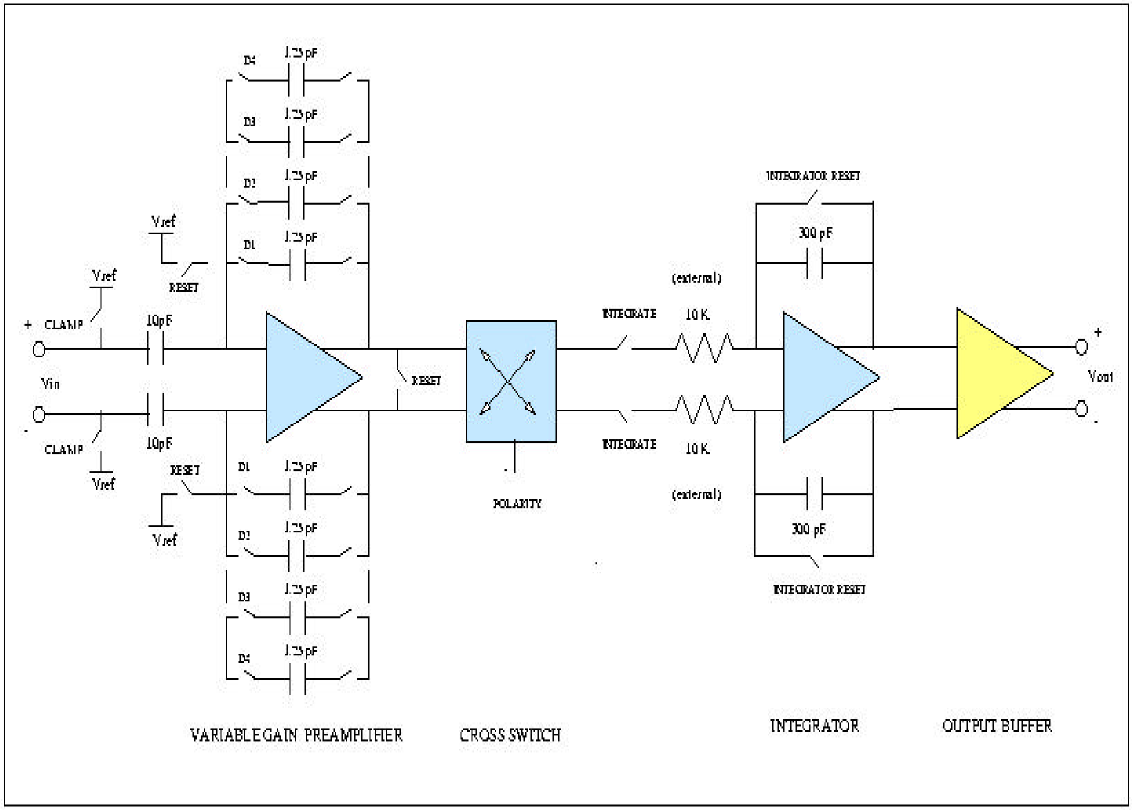
•**DAQ and instrument control interface** – Path to data buffer memory, master timing, and configuration and control.

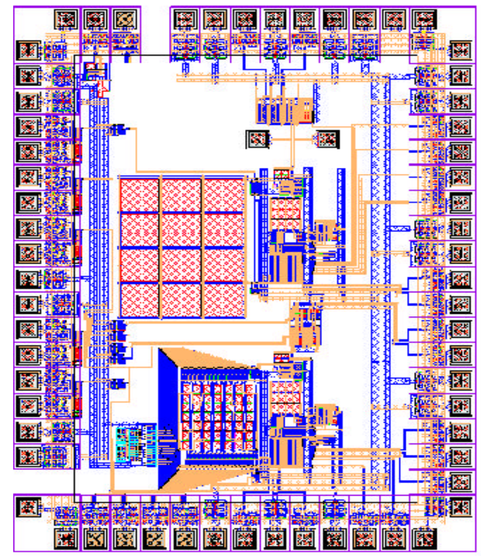


CDS ASIC

LBNL has a long history in rad hard ASIC design for high energy physics.

- **We have submitted a CDS to DMILL.**

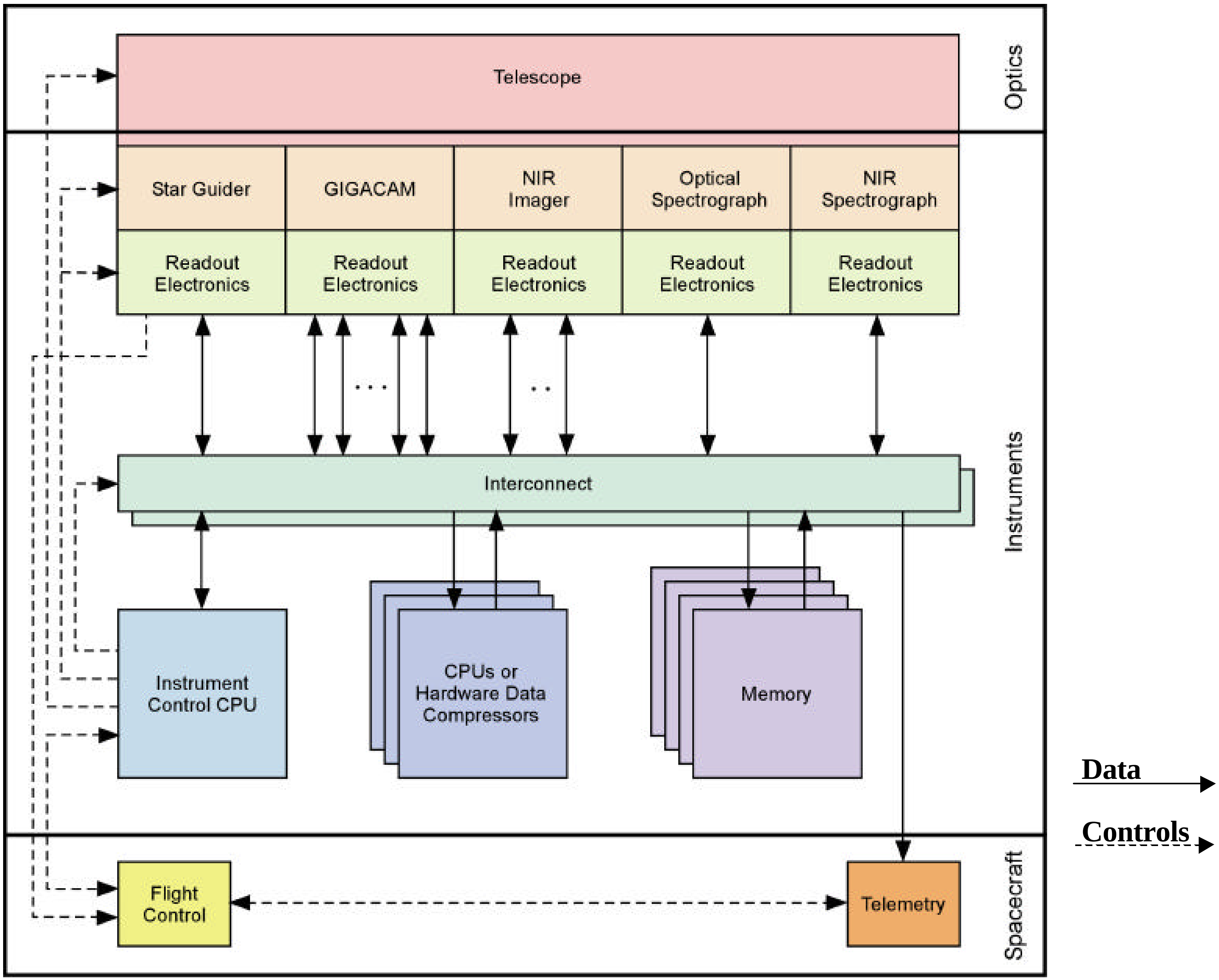




Recent developments

- **0.25 mm TSMC (IBM compatible) parts have shown no damage to 30 MRad.**
- **We have tools to directly synthesize digital rad hard devices.**

Data Acquisition



Data Acquisition continued

Data sources

- GigaCam 150-236 1 MB/s data streams active for 20 s every 120 s.
- NIR imager 1-24 0.2 MB/s data stream active for 10 s every 100 s.
- Spectrographs 0.2 MB/s data stream active for 10 s every 100 s.

Data buffering

- Collect data streams into buffer memory.
- Data will be lossless compressed by at least x2.

Data processing

- Transmit all exposure data to the ground.
- 250 GB/day to ground with x2 data compression.

Observation program execution

- Ground-developed script generated by SNe discoveries.
- Local intelligence maps the abstractions of the script into instrument control commands.

Conclusion

Goals that we can achieve with LBNL CCD technology:

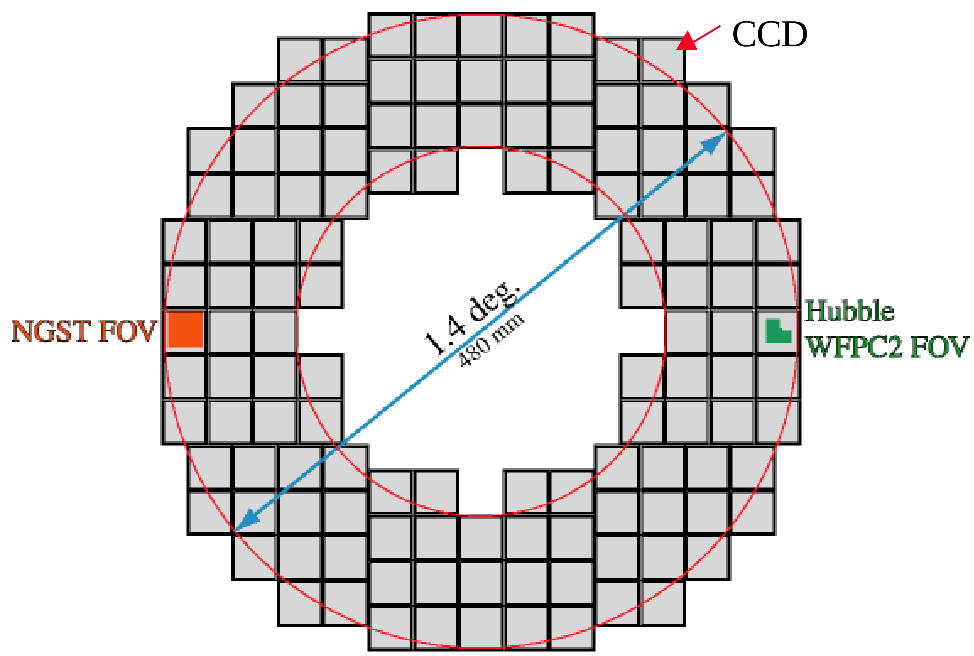
Populate 1° x 1° focal plane with small dead space. 88% packing efficiency.

Broad spectral response with high quantum efficiency. High QE from 350 nm to 1000 nm.

Low read noise to allow stacking multiple exposures. 2e$^-$ at 100 kHz read rate.

Low dark current to allow long exposures. 0.001 e$^-$/s.

Stable performance in presence of >3 years radiation. Radiation tolerant charge transfer efficiency, dark current, and read noise.



Moon